REVIEW ARTICLE

Virtual Articulators versus Conventional Articulators: A Review

Dr. Pankaj Murkut[1], Dr. Rumiya Ayesha[2], Dr. Himanshu Srivastava[3*], Dr. Aditi Subhashchandra Sarda[4]

[1]Postgraduate Student, Prosthodontics, Crown Bridge & Implantology, Aditya Dental College, Beed, Maharashtra, India
[2]Reader, Department of Prosthodontics, Crown Bridge & Implantology, Aditya Dental College, Beed, Maharashtra, India
[3]Professor & HOD, Department of Oral and Maxillofacial Pathology and Microbiology, Aditya Dental College, Beed, Maharashtra, India*
[4]Reader, Department of Conservative Dentistry and Endodontics, Aditya Dental, College, Beed, Maharashtra, India

Corresponding Author: Dr. Himanshu Srivastava*

ABSTRACT
Articulators are essential in prosthodontics for diagnosis, treatment planning, and fabrication. Outside the mouth, the only way to study static and dynamic relationships of the occlusion is with articulators. Mechanical articulators have some limitations. First, they rely on a user to follow the recorded movements of the condyle and mandible. Accuracy is limited by the mechanical simplification of the mandible and the condylar guidance. Recently, some of the limitations of mechanical articulators have begun to disappear with the introduction of intraoral scanning, cone beam imaging, facial scanning, and tracking the motion of the jaw. Virtual articulators have come on with digital casts that are placed in a common coordinate system and then articulated using the rules of computer aided design and computer assisted manufacturing. The goal of this narrative review is to compare and analyze the two systems based on the principles of operation, data acquisition and mounting, movement simulation, occlusal analysis, accuracy, error profiles, and clinical application. The recent evidence, primarily from laboratory and in vitro studies, shows that virtual articulators achieve comparable results for trueness and precision when the same data are used as mechanical articulators. Results vary across software applications, and the results deteriorate when occlusal stability is compromised. Clinical studies that isolate articulation from fabrication methods are very rare. The introduction of virtual articulators has moved the sources of errors, but has not completely eliminated these errors. Digital articulators are complementary to standard articulators. The clearest advantage of the virtual articulators is their ability to store digital records, replicate dynamic contacts, and be integrated with computer aided design and computer aided manufacturing.

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INTRODUCTION

Occlusion is an important factor for the functionality and biology of almost every prosthodontic restoration. It determines whether a prosthesis is tolerated or repeatedly modified. The relations involved cannot be examined properly within the oral cavity. Therefore, the profession has been reliant on prostheses that re-create these relations outside the patient. An articulator is a mechanical representation of the temporomandibular joints and the jaws in which maxillary and mandibular casts may be attached in order to facilitate some or all mandibular movements [1]. It is used in diagnosis and treatment planning and fabrication of the prosthesis. It is used to study reversible and non-reversible changes in the occlusion [2].

Digital dentistry reframes the question rather than answers it. Scanning technology integrates multiple scan devices to combine and synthesize intraoral scans, cone beam CT scans, facial scans, and scans of the jaw motions into a single three-dimensional scan. In this integrative environment, the articulator becomes software[3]. From the first software articulators of the early 2000s, virtual articulators were constructed to analyze static and dynamic occlusion of software reproduced digital models. They advanced subsequent developments toward software articulation and manufacturing. Today, with digital design, a virtual articulation is a prerequisite to the design of a prosthesis. Virtual articulators are now integrated in clinical practice[4].

External software articulators are on the market. Vendors claim that virtual articulators reduce the time for manufacturing articulated models and simplify the articulation process. Subsequent reviews analyzed the comparison of the clinical outcomes of mechanical and digital softwares and articulators[5]. The validity and the

**Author for Correspondence: himanshu.srivastava97@gmail.com*

reliability of digital articulators are unclear. Clinical research using digital articulators is sparse. Currently, an exhaustive review combines principles and methods, assesses the accuracy and assesses the clinical use of both mechanical and digital articulators and attempts to determine whether they are complementary or substitutive[6].

Conventional Articulators

Definition and principle

A conventional articulator is a mechanical substitute for the craniomandibular complex. It consists of two rigid parts, joined posteriorly by condylar elements and separated anteriorly by an incisal pin[7]. Casts that represent the patient are positioned in this relationship, and the lower part of the articulator is constrained by two elements: condylar guides and an incisal guide table. The simplicity of the design of the articulator means that the movements of the casts are constrained to a limited number of movements compared to the complex movements performed by the mandible. The fidelity of the articulator depends on the determinants and the level of precision with which they are recorded [8].

Types and clinical importance

Simple hinge articulators allow rotation about a fixed axis and are therefore limited to cases in which the occlusal relationship remains undisturbed. Mean-value articulators are used with fixed average values for condylar and incisal guides, which are appropriate for standard routine work for patients in the 'average' population[9]. Semi-adjustable articulators use a facebow record and allow adjustment of sagittal condylar inclination, Bennett angle and, in some designs, mandibular translation and intercondylar distance[10]. These articulators are the most commonly used in standard fixed and removable prosthodontics. Fully adjustable articulators use a pantographic or axiographic record, and, to the best of the operator's ability, simulate the individual characteristics of the condylar pathway [3,10].

Components and workflow

Figure 1 shows the primary elements. Upper and lower members carry the casts through mounting plates and mounting stone through upper and lower members. Posterior condylar spheres move in slots with inclinations that dictate the path of protrusive and lateral movements. In the anterior region, the incisal pin contacts the incisal guide table, which controls the vertical dimension and anterior guidance. A facebow connects the maxillary cast to the arbitrary or kinematic hinge axis and to a horizontal reference plane. The clinical process includes the production of impressions and casts, the transfer of the facebow, and the placement of an interocclusal record for assembly, programming, occlusal analysis, fabrication by the laboratory, and verification in the mouth. Each stage has its own tolerance.

Advantages and limitations

When compared to other instruments, the articulator is the most widely used and the most researched. The necessary processes are standardized and users insert casts so they can manipulate the articulating foil and shim stock to their satisfaction. The articulator requires no digitization and works well with the routine lab processes [2].

Its limitations are mechanical, not conceptual. A semi adjustable instrument reproduces a simplified envelope defined by rigid guides and cannot represent the resilience of the soft tissues, muscular control, or the time dependent chewing movements of the living patient[11]. In addition, error is introduced upstream through the impression, the resulting gypsum distortion, the thickness of the interocclusal record, and the mounting technique[12].

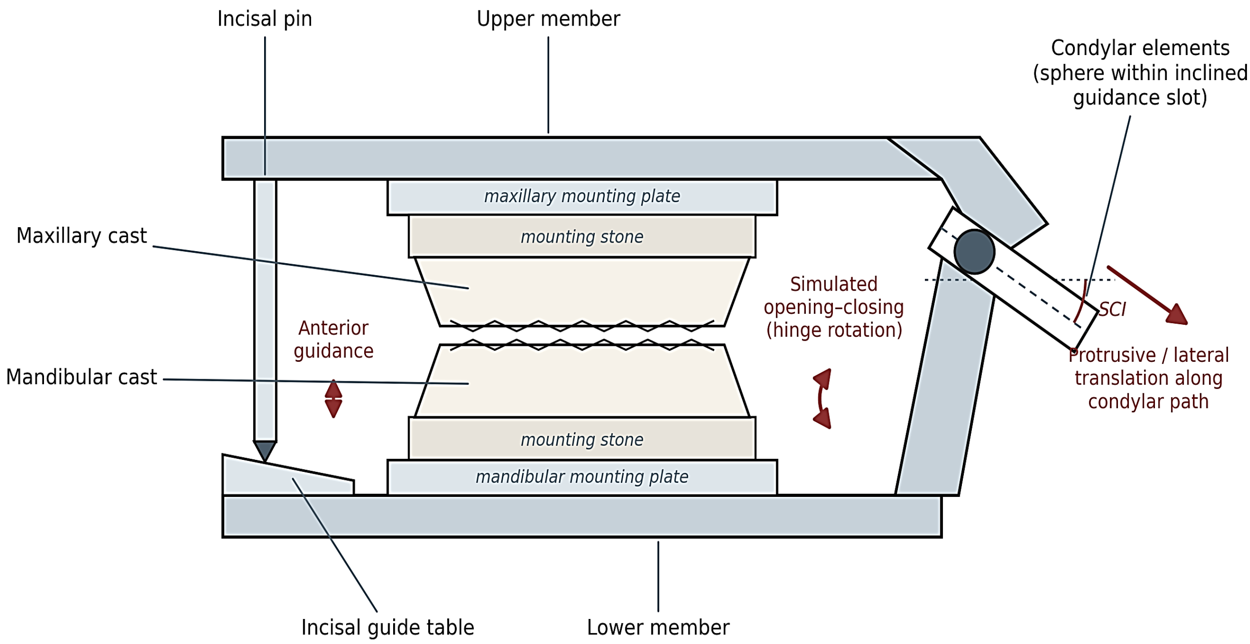

Figure 1. Basic design of a traditional jaw movement machine. Differentiating members for maxillary and mandibular casts are joined via mounting plates and mounting stones. The lower member of the machine consists of a condylar sphere which moves on a sloped track that allows lateral movements. An incisal pin contacts an incisal guide table on the upper member of the machine and controls the vertical dimension of the articulator and limits the anterior guidance. The movements that the instrument is intended to mimic are shown by the red arrows

Facebow systems do introduce measurable amounts of error, and in vitro studies indicate that different design approaches can result in different maxillary occlusal plane positions for a given patient [13]. In addition, wear and loose mounting surfaces, and inappropriate programming, increase the variability. Physical models cannot be duplicated without distortion. There are no critical assessments that indicate that common types of articulators are not accurate. At best, the assessments indicate that, in the context of articulators, accuracy is limited and dependent on the operator[14].

Virtual Articulators

Definition and principle of operation

Virtual articulators allow for the manipulation of digital casts in a defined coordinate system using prescribed kinematic rules. Virtual articulators differ from mechanical articulators in the absence of physical constraints[15]. This allows a user to adjust the constraints of a digital simulation.

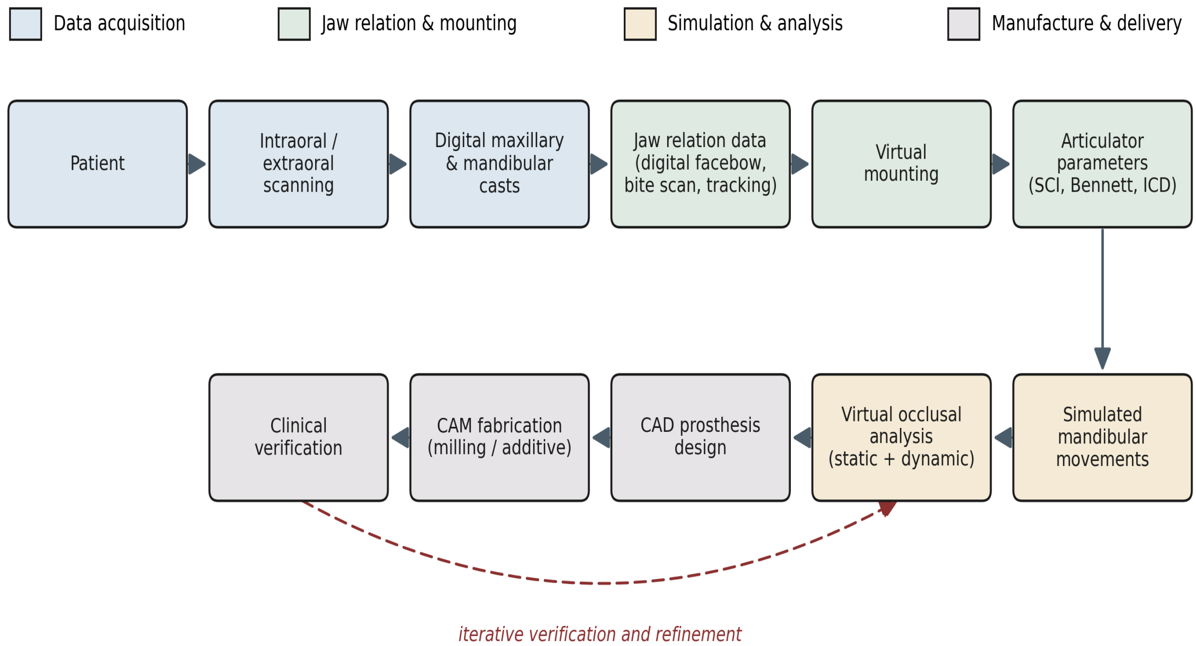

Figure 2. Virtual articulator digital workflow for patient data collection and virtual mounting, parameter setup and occlusal analysis, virtual design, manufacturing, and clinical evaluation. Workflow modules are differentiated by color. Different color modules represent different workflow stages: acquisition, virtual mounting, analysis and manufacturing. Clinical evaluation provides ongoing inputs to analyze and refine the virtual occlusal analysis. SCI: sagittal condylar inclination; ICD: intercondylar distance

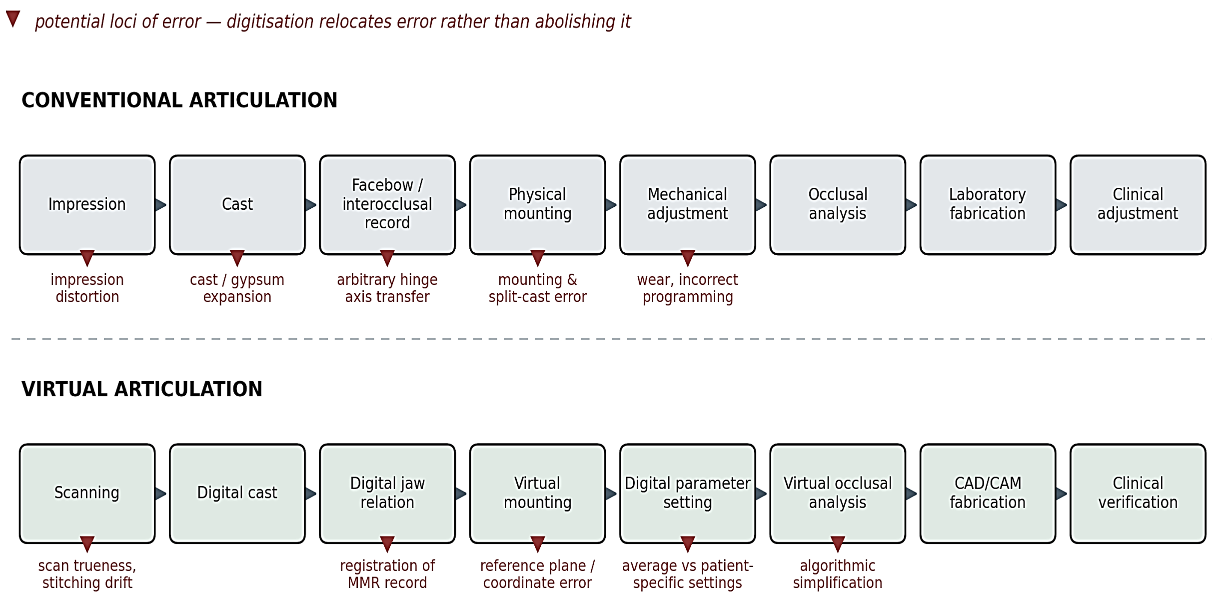

Figure 3. Comparison of the principal stages and potential errors in the conventional and virtual articulation workflows. The comparison demonstrates that digitization transfers error from material and mechanical sources to optical, registration, and algorithmic sources. It primarily means that digitization does not eliminate error. MMR, maxillomandibular relationship

Though this removes wear and friction, it increases the dependence on input data and assumes the validity of the algorithm[16].
Evaluation of digital casts can be performed after an intraoral scan or a conventional cast has been digitized. The maxillomandibular relationship can be established using an interocclusal scan or tracked jaw position[17]. Finally, digital facebow procedures can be performed to orient the maxillary cast in relation to a reference plane. Typically, default values are assigned to the condylar parameters (i.e. Bennett angle, sagittal condylar inclination, and intercondylar distance). These values can be determined from protrusive scans that are supplemented with cone beam imaging or extracted from measured trajectories. With this information, the software determines the proximity or penetration of surfaces across the excursive range[14].

Classification

The terminology used in the literature and by manufacturers is not standardized, and a universally accepted classification system does not exist. Technologically, three levels can be distinguished: systems that evaluate contacts in a static position only; systems that evaluate the parameters of a semi-adjustable mechanical system; and systems that allow for the movements of a mechanical articulator to be extended. Not all features of a mechanical articulator are present in virtual articulators, and the absence of a feature is not always apparent to the user [13].

Data acquisition and workflow

The virtual articulator is limited by the datasets built within it. Intraoral scans capture dental surfaces. Extraoral scanning, impressions, or casts can capture surfaces indirectly. Scanning facial surfaces and taking photos with standardized references capture facial surfaces, cone beam imaging captures the mandible and the skeleton, and motion capture systems capture jaw movements [15]. Digital facebow techniques have been classified based on the acquisition technique and have been shown to significantly vary in accuracy by the authors that studied them [16]. Some techniques have at the core a scanning process, and accuracy of such techniques has been studied and significant differences in accuracy have been observed [17]. There is evidence that “face bow techniques” can be designed to eliminate the need for the physical facebow and minimize the deviation [18]. Registration hinges on the shared dental landmarks that must be sufficiently distinct to minimize registration error.
The process is illustrated in Figure 2. Following acquisition and the generation of the digital casts, maxillomandibular registration, virtual mounting, definition of the parameters, and a simulation of the movement and analysis of the occlusion are performed. The dataset is then utilized for design, fabrication, and shipment of the physical model, without the need for re-digitization. There is a verification loop in which the clinical findings are sent to the analysis stage since the only direct measure of the simulation’s accuracy is intraoral adjustment.

Advantages and Limits

Reproducibility is improved by digital articulation over analog articulation. Digital articulation does not degrade the original dataset when it is duplicated and shared, as occurs with mechanical analog articulator. In digital articulation, occlusal relationships are not represented by marks and thus are not inferred. Instead, the relationships are shown as a color-mapped distribution and the contacts are visible on the excursion. By far the greatest advantage is the ability for direct integration of articulation data into design; this eliminates the need for digitization [9, 15].
These advantages have conditions. The workflow is dependent on scanner performance and software and hardware licensing, as well as training to identify unreliable datasets. Digital casts have scanning errors, and complete-arch scans have stitching deviation. Virtual mounting is dependent on the accuracy of the reference plane and interocclusal registration. There is a lack of clinical evidence on long-term performance. [10,11].
Even the best digital dental restoration systems have issues. Different systems can have various movements and different file formats. There just isn't much good evidence on the clinical long-term effects of using dental restoration systems. [10,11].

Conventional versus Virtual Articulators

Table 1 shows a comparison of the two systems. This discussion explains these differences in terms of how they impact clinical decision-making.
The two systems have different constraints and therefore different approaches to casting and movement. A mechanical articulator uses physical guiding and casting, while a virtual articulator uses a casting position prediction algorithm. Neither of these systems models the patient. In the case of virtual models, where some of the values are averaged, the system inherits the restraint common to all average-value mechanical systems, while presenting output in a format that may seem to be highly accurate and precise, when in fact the underlying data may not support this [10,13].
In terms of the data captured and the process of mounting, significant differences become apparent. In the case of the more traditional system, errors typically result from the behavior of the material, distortion of impressions, the expander, and the technique of mounting. In the case of the more digital system, errors result from distortion of optical scanning, distortion of registration, and a poorly defined reference plane[19]. The errors resulted, but the location of where these distortions impact the system is different; this is important when considering the process of ensuring the quality of the system. For example, an verification of a split cast detects a poorly constructed mounting, but this verification does not detect a poorly constructed digital registration[20].
This becomes apparent when considering facebows as an example. In the more traditional system, errors result from placing arbitrary hinges and horizontals and large measurable differences in the systems. In the more digital systems, errors can result from using different types of references that have different accuracy profiles, such as photographs, facials scans, radiographs, and tracked references[21]. In both cases, the placement of the reference plane determines the orientation of the maxillary cast and therefore the path of movement of the mandibular cast.

Table 1. Comparison of conventional and virtual articulators in prosthodontics

Parameter	Conventional articulator	Virtual articulator	Clinical implication
Basic principle	Mechanical constraint of casts by physical guidances	Computed cast positions from a kinematic model	Both are approximations; the model of movement, not the medium, sets fidelity
Representation	Physical casts in real space	Surface meshes in a virtual coordinate system	Digital records can be duplicated and shared without physical transport
Data acquisition	Impressions and gypsum casts	Intraoral/extraoral scans, digitised casts, CBCT, facial scans	Material distortion is replaced by optical scanning error
Cast mounting	Manual mounting in stone against mounting plates	Software alignment to a defined reference plane	Mounting variability becomes registration and reference-plane variability
Facebow transfer	Arbitrary or kinematic mechanical facebow	Photographic, facial-scan, CBCT or tracking-based digital facebow	Reference plane selection determines maxillary cast orientation in both
Jaw relation record	Wax, polyvinyl siloxane or resin interocclusal records	Digital interocclusal scans or tracked jaw positions	Record extension and occlusal stability affect accuracy in both systems
Condylar simulation	Adjustable physical condylar guidances	Assigned parameters or recorded movement trajectories	Only motion-tracked input approaches patient-specific dynamics
Incisal guidance	Incisal pin and customisable guide table	Virtual guidance parameters or scanned anterior morphology	Digital customisation is faster but requires accurate anterior data
Occlusal analysis	Articulating foil and shim stock; visual and tactile	Colour-mapped proximity analysis, static and dynamic	Digital maps show geometry, not occlusal load on resilient tissue
Accuracy (evidence)	Long clinical track record; transfer errors quantified	Comparable in vitro trueness and precision; system dependent	In vitro equivalence must not be read as clinical superiority
Reproducibility	Limited by remounting and mechanical wear	High; identical dataset can be reopened indefinitely	Supports longitudinal comparison and structured documentation
Error sources	Impression, cast, facebow, mounting, wear	Scan, registration, reference plane, parameter, algorithm	Digitisation relocates rather than eliminates error
Time and workflow	Multiple physical stages and transport	Fewer physical stages; immediate data transfer	Efficiency gains depend on operator proficiency and system maturity
CAD/CAM integration	Indirect; casts must be digitised	Native; articulation data feed design directly	The principal practical advantage of virtual articulation
Record storage	Physical casts and mountings requiring space	Digital archiving with backup and retrieval	Reduces storage burden but introduces data-governance duties
Equipment and cost	Modest outlay; widely available	Scanners, licences, hardware and maintenance	Cost-effectiveness depends on case volume and workflow maturity
Learning curve	Familiar to most clinicians and technicians	Requires training in scanning, software and error recognition	Operator competence determines outcome in both systems
Clinical verification	Intraoral assessment and adjustment at delivery	Intraoral assessment and adjustment at delivery	Verification remains mandatory irrespective of articulation method

At the cutting edge of virtual articulation is condylar simulation with particular demands. A semi-adjustable virtual articulator programmed to use average values provides zero kinematic advantage over its real-life counterpart; the system driven by recorded jaw motion data replaces assumed with measured movements and is entirely different [4,20]. This is often overlooked when virtual articulators are discussed as one system and contributes to most of the issues observed in the published literature.

Accuracy and Sources of Error

Figure 3 shows key sites of error for both workflows. Where error occurs is usually linked to distortion of impression, casting, arbitrary choice of hinge axis and thickness of interocclusal record, and is further influenced by mounting procedure, wear of articulator, and incorrect programming; these are well understood and can be detected by the existing verification techniques. Error is relocated through digitization, meaning that elimination of some steps of the workflow can introduce error in other steps. The goal should not be to choose the workflow with the least number of error sources, but to select the workflow whose errors can be assessed and managed, to perform verification as necessary, and to adjust the workflow to optimize the available methods in a particular setting [21].

Clinical Applications
In complete denture prosthodontics, articulation establishes either a balanced or lingualized position and the stability of the prosthesis. Digital workflows have been established for this. However, the benefits that have been recorded primarily concern the ease of manufacture, reduction in the number of visits and the durability of the records, rather than the articulation itself [22]. Traditional articulation has its merit where the jaw relation is difficult to capture in a digital format for an edentulous patient.
In fixed prosthodontics, in the context of single unit and short span restorations in a stable occlusion, virtual static articulation can be justified, and this is supported by the best available evidence [11]. In the context of implant-supported restorations, in the absence of significant proprioception, incorporation of recorded mandibular motion to reduce excursive interferences has been investigated [3]. In the context of removable partial dentures, the constraints of intraoral scanning technology mean that traditional methods must continue to be used[20].
In contexts of occlusal rehabilitation and full-mouth reconstruction, dynamic virtual articulation is clearly indicated, as the extent of likely occlusal changes means that the least defensible value for the position of the condyle can be assumed, and the digital record can be placed over existing and proposed prostheses. The same datasets can be used for the planning of aesthetics and dynamics of treatment in the context of multiple specialities, as the virtual patient can be explored[22].
Clinical Evidence
This evidence should be read taking into consideration study design as most of the comparative work is in vitro. In a laboratory study using typodonts that were mounted on a semi-adjustable apparatus, the virtual movements were as accurate and as precise as movements that were created mechanically. Deviations of less than 100 µm would be clinically irrelevant [4]. Static articulation studies show trueness and precision within clinically acceptable ranges and are dependent on the scanner and design system used [5].
Not all laboratory studies favor digital articulation. One study compared digitally articulated milled models to conventionally articulated stone casts. A significant difference was seen in the occlusal contact area of one anterior tooth, and the digitally articulated group demonstrated more uneven anterior contact, indicating that buccal-scan articulation may not distribute contacts in the same way as hand articulation[15]. On the other hand, one study reported a high correspondence of contact in both the number and position of analogue and digital contacts, indicating that the registration step may not be the main limiting factor [7].
Two meta-analyses have attempted to synthesize the evidence. One of the two concluded that the accuracy and precision of virtual articulators is comparable to that of mechanical articulators in the absence of definite answers due to the great variation in software and techniques [10]. The other, focusing on static articulation, indicated that, in favorable situations, acceptable accuracy is achieved, while, in other cases, accuracy is critically lacking [11]. Another recent systematic review focusing on both static and dynamic simulation has been published [12].
Research on specific articulation methods is lacking because most clinical literature focuses on comparisons of digital and traditional articulation methods as a complete system[18]. With respect to complete dentures, a meta-analysis concluded that, in terms of clinical outcomes, there was no statistically significant difference in patient satisfaction between manufacturing methods, and in some cases prosthesis made using digital fabrication outperformed those made using traditional methods; however, a randomized cross-over study noted that the digitally fabricated prosthesis scored significantly lower than traditional methods for quality of denture assessment[12]. In general, there are many methodological inconsistencies that account for the disparities in the results. These include differences in research frameworks, smaller sample sizes, poor integration of software, and conflation of articulation with manufacturing[20].

DISCUSSION

Virtual systems do provide some advantages and these are not related to kinematics. The first is reproducibility. An articulation that was done several years prior can easily be reopened. The second is integrative capability. Articulation and design can be done in the same environment. Relationships of excursion can be designed to inform the position of the occlusal surface that will be fabricated, rather than being adjusted after fabrication[12]. Visualization is the third, but contact maps represent geometric proximity, and occlusal contacts represent a combination of geometric and material properties.
Errors that persist after digitization should be emphasized. The maxillomandibular relationship still needs to be captured, with the same level of accuracy being dependent on occlusal stability and registration[20]. Digital facebow methods vary in how well they are able to align the maxillary cast to a reference plane. The clinician who assumes a digital workflow is self-verifying is making the same mistake as a clinician who assumes a facebow record is exact[18].
In the absence of complete control of the virtual articulators, chewing is a muscle-coordinated, load-regulated, and signal-regulated process, as well as being food bolus dependent. Border movements that are recorded in an unloaded state are just an enveloping movement and do not approximate a true function[21]. Digital sophistication improves the results of a prospective treatment only if it eliminates a genuine constraint in the treatment result, and within a single crown in a stable architecture, condylar fidelity would rarely be the constraint[22].
Clinician experience is still important in both conventional and digital workflows. Skill in impression making, record taking and mounting is required for the former, whereas skill in scanning and the ability to interpret software output is important for the latter[11]. Extensive occlusal reconstruction and implant-supported restorations are the most common clinical cases which benefit from virtual articulation. In the absence of virtual articulation, conventional articulation should be used for routine

restorative cases in an occlusion which is stable, removable prosthodontic cases which rely on the support of surrounding soft tissues, and when the quality of digital data cannot be assured. Inconsistencies are prevalent across reviews. There are few prospective studies, outcome measures are not standardised and there is little long-term data on dynamic virtual articulation [12].

FUTURE PERSPECTIVES

The next phase of interactive planning will involve several changes. Intraoral scanning and cone beam imaging can be used in combination with high-speed cameras to create a dynamic virtual patient in which the dentition, the skeletal structure, and the motion can be integrated [4,5]. It will also be possible to integrate several digital facebow systems into a single platform using a standard reference frame [18]. The application of occlusal analysis and interference detection to artificial intelligence will facilitate the refinement of automated design and the transition to automatic adjustment of occlusion[11].

The researched guidelines contain several areas of potential, as opposed to established, truth. Validation steps against clinical adjustment will be necessary to bring automated occlusal design to a verified state. Additionally, the creation of a digital version of the chewing system is hampered by modeling the control of the chewing muscles and the elasticity of the chewing tissues. The field will make more progress with the use of platforms that are more interoperable and transparently report the assumptions of the simulations and controlled studies than with the introduction of more complex programs[22].

CONCLUSION

Virtual articulators and manual articulators function side by side. Traditional methods of articulating are still best suited for most of restorative prosthodontics, but may be substantially improved for other treatments. Using artificial trueness and precision, virtual articulation may fill in for articulators in certain situations; however, the digital equivalent of manual trueness and precision still has many variables, and it is not an equivalent substitution. Virtual articulation has many advantages including digital recordability, replicability, and design integration. Its greatest deficiency is reproducing the complexity of jaw movements. In terms of error, digital technologies do not eliminate error; they simply introduce new sources of error. Evaluating the difference in articulation on the methods of jaw movement has been limited. Traditional articulators have their place in routine clinical therapy, while virtual articulators are most useful for complex occlusal reconstructions. The outcome of any digital articulation method will be a clinical combination of case selection, data quality, operator experience, and verification of the clinic.

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